Fully polarimetric W-band ISAR imagery of scale-model tactical targets using a 1.56THz compact range

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ABSTRACT

With the continuing interest in ATR, there is a need for high-resolution fully polarimetric data on tactical targets at all radar bands. Here we describe a newly developed system for acquiring W-band data with 1/16 scale models. The NGIC sponsored ERADS project capability for obtaining fully polarimetric ISAR imagery now extends from X to W band.

The high-frequency terahertz compact radar range developed recently to measure single polarization return from scale models of tactical targets has been enhanced to collect fully polarimetric data. The 1.56THz transceiver uses two high-stability optically pumped far-infrared lasers, microwave/laser Schottky diode side-band generation for frequency sweep, and a pair of Schottky diode receivers for coherent integration. Tactical targets may be measured in "free space" or on various ground terrain, which simulate different types of terrain. The results of recent polarimetric measurements on several tactical targets will be presented. Data collected using this compact range from a simulation target will also be compared with predictions from the XPatch computer code. In addition to conventional ISAR imaging the compact range is capable of imaging in both azimuth and elevation by collecting data and integrating it through a solid angle. Recent two-dimensional and three-dimensional measurements using this technique will be presented.

Keywords: Sub-millimeter, Radar, Imagery, Modeling.

1. INTRODUCTION

In recent years, the goal of the Expert Radar Signature Solutions (ERADS) project has been to provide fully polarimetric, high-resolution radar data on tactical targets for many radar bands of interest. With the continuing interest in automatic target recognition (ATR) and for comparison to computer code predictions, there has been an increasing need for such data. Compact ranges have proven their usefulness towards this goal in their ability to collect data by measuring scaled models of targets under controllable conditions. The Submillimeter-Wave Technology Laboratory (STL) at UMass Lowell has developed several compact ranges that model the current radar frequencies of interest.[1] ERADS can now collect fully polarimetric data from X-band to W-band.

Since the technique was first demonstrated in the submillimeter-wave region in the late 1970's,[2] radar measurements made on target models using scaled frequencies have continued to grow in interest. These early systems were based on optically-pumped submillimeter lasers and bolometric detectors. At frequencies up to 0.75THz these systems are now being replaced by solid state tranceivers which use frequency multiplication of synthesized microwave sources. However, above about 1THz there are presently no suitable alternatives to the power and stability of a laser-based source. STL has improved and refined these laser-based systems for high-frequency measurements by the addition of Schottky diode sideband generators and heterodyne receivers to provide a wide-band capability and coherent detection at THz frequencies. These ultra-stable laser systems have very good phase and amplitude stability with a typical phase drift of 4° / hour. The new W-Band compact range operates at 1.56THz and can collect fully polarimetric data. Since the positioning of the target can be controlled with a high degree of precision, the compact range is able to collect data for both two-dimensional and three-dimensional imaging.

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2. THE 1.56THZ COMPACT RADAR RANGE

Although the fully polarimetric W-Band compact range is a modified version of the compact range previously described,[3] sufficient differences exist to warrant a full description here. To model W-Band at 16^{th} scale a very high stability 1.56THz laser has been developed. Figure 1 shows the diagram of the 1.56THz compact range. The source consists of two 150 Watt, ultra-stable, grating-tunable CO_2 lasers, which are used as the optical pumps for the two far-infrared lasers. The CO_2 lasers are set to produce $9\mu m$ (9P22 CO_2 laser line) and $10\mu m$ (10R10 CO_2 laser line) wavelengths respectively. The output of these lasers are then used to pump the laser transitions in the molecular gases difluoromethane (CH_2F_2) and methanol (CH_3OH) at 1.5626THz and 1.5645THz respectively.

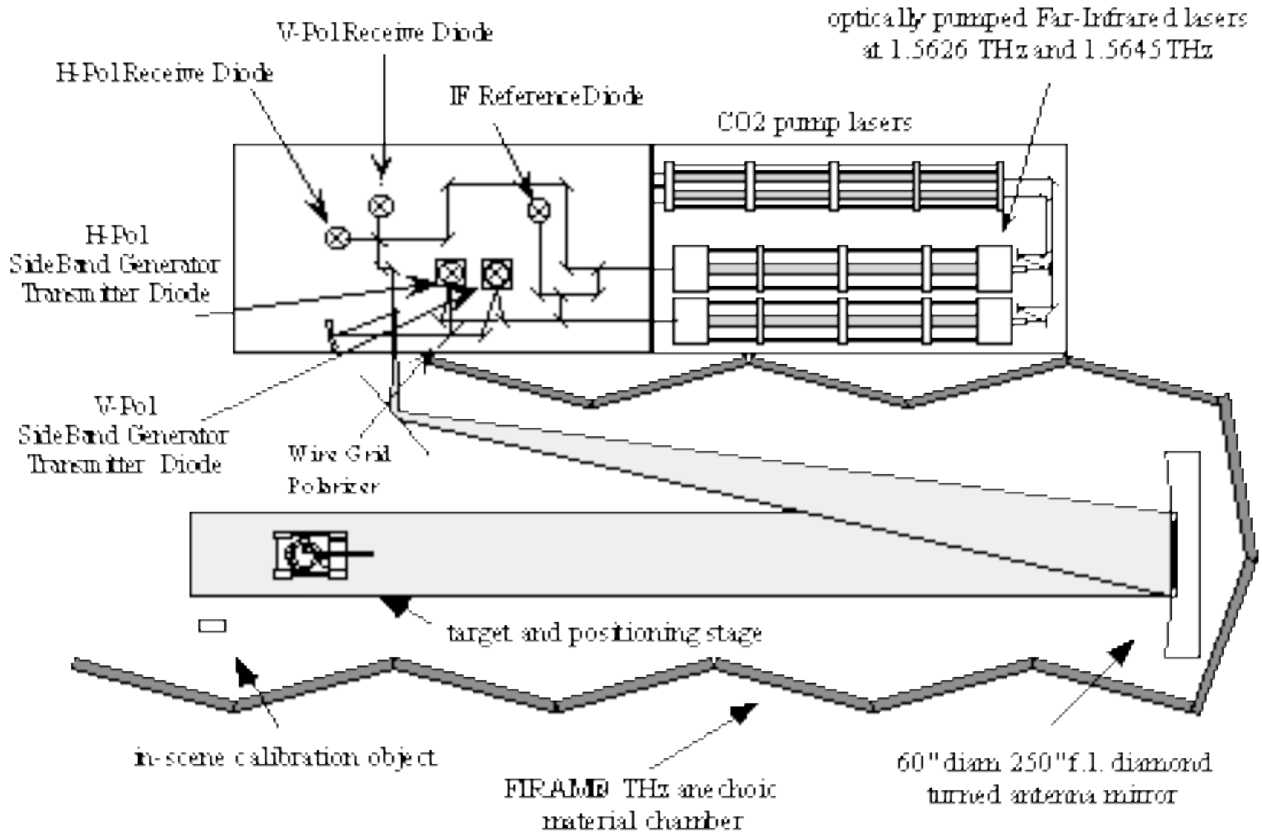


Figure 1. Diagram of the 1.56THz compact radar range.

The far-infrared lasers produce gaussian modes with 10mm diameter full width at half maximum (FWHM) cross-section output beam and typically 100mW of power. One laser is used as the base transmitter frequency which can be used in single frequency mode or mixed with an external microwave source to generate a range of frequencies. The other laser serves as the receiver local oscillator. The transmitter beam is propagated to the target range and is collimated by a 60" diameter, 250" focal length mirror before illuminating the target. Radiation that is back reflected from the target is collected and mixed with the local oscillator using corner-cube-mounted Schottky diodes as heterodyne receivers. The receiver can simultaneously detect both vertical and horizontal polarization returns from the target by use of a wire grid, which reflects horizontal polarization into the H-Pol diode, or transmits vertical polarization into the V-pol diode.

The transceiver has a two way FWHM beam diameter size of 20" corresponding to a beam diameter size of 26' on the full-scale target. This is sufficient to provide complete illumination of typical scale models. Larger targets have also been measured using this technique. A gaussian correction of the beam taper can be taken into account when necessary. The models are mounted on a low cross section pylon. The pylon is set in the middle of a range whose walls are covered with an anechoic material (FIRAM®) specifically designed for THz frequencies. This is done to minimize the amount of radiation scattered back into the receiver by objects other than the target. An in-scene calibration object is also located in the beam at a

different range from the target in order to provide a signal with which to monitor and correct for phase and amplitude drifts of the system. The system is slightly bistatic, with a bistatic angle of 0.3.˚

The far-infrared lasers produce very stable narrow-band frequencies with short-term drift ≤ 50KHz ($\Delta\nu/\nu \approx 10^{-8}$). The output of the transmitter laser can be used directly to make very high sensitivity measurements of the radar cross-section (RCS) of the target. This mode of operation offers the best possible signal-to-noise since it makes use of the full power of the transmit laser. This technique does not allow range to the target to be measured. Although care has been taken to minimize unwanted signal in the system, background radiation scattered from the edges of the optical components, back wall of the range, and target supports can still be seen. However, introducing a controlled motion of the target and performing a Fourier analysis can isolate the background signal. This technique has produced images with noise floors as low as -65dBsm per image resolution element. If the controlled motion of the target is a precise variation in azimuth and elevation, complex data can be taken and Fourier transformed to produce very high resolution images in azimuth cross range and elevation cross range (Az/El imagery). Examples of this will be given in the following section.

In addition to the use of the narrow-band laser output for the transmitter, a technique has been developed[4] whereby a tunable frequency is generated. The transmitter FIR laser is focused onto two Schottky diodes mounted in corner cubes. The transmitter laser frequency is mixed with the output of a 10-18 GHz microwave sweeper. This technique produces two sideband frequencies that can be swept and are separated from the original laser by the frequency of the microwave source. The receiver electronics are designed to only detect the lower sideband frequency by a frequency-shifted, asymmetric down-conversion. In order to measure the full polarimetric scattering of the target, one of the sideband generators is designed to transmit horizontal (H-pol) and the other is designed to transmit vertical (V-pol). Using a phase delay line between the two transmitters and combining them along the same propagation path by use of a wire grid polarizer, it is possible to transmit and receiver all four polarization combinations (VV, VH, HV, HH) simultaneously thus simplifying the data collection operation. When a linear sweep of the frequency is performed the range to the target can be calculated with a range resolution of 10" at full scale. Using Fourier analysis the target can be sub-resolved in range. This technique also allows the target to be easily separated from other background signals. Since the sideband generation is limited by the efficiency of the Schottky diode mixer, the total amount of transmit power is reduced to approximately 5μw. This is sufficient power to form ISAR images with typical noise floors of -30dBsm per image resolution element.

Since the data taken is fully polarimetric, the calibration method described by Chen[5] has been used to calibrate the system before each data run. This method uses several high quality calibration objects whose polarization responses are well known. Before each data run, the system measures a flat plate, vertical seam dihedral, and dihedral with seam at approximately 22.5.˚ Transmit and receive correction matrices are then calculated to obtain the correct polarization response from these reference objects.

3. Results

3.1. Comparison of results with computer code prediction.

Whenever possible, it is useful to compare measured results with previous works. Although there have been relatively few field measurements at W-Band on targets, the XPatch computer code has been used successfully in a previous study[6] at lower frequency to predict the radar return from a complex target simulator (the T5M3). This target has been found to produce scattering complex enough to test the quality of data from the lower frequency compact ranges while providing the computer codes with a geometry simple enough for XPatch to calculate in a reasonable amount of time. Since the T5M3 has been studied in this way at lower frequencies and since it provides a variety of multi-bounce scattering it was used as the test subject. Full details of the T5M3 can be found in Ref[6].

Figure 1 shows the results of the comparison between the measured and predicted RCS for H transmit H receive for a 10 degree elevation angle. Figure 1(a) shows the measured HH RCS at 0.01˚ angular increments. The inherent scintillation in the measured RCS makes it difficult to display the XPatch predictions on the same graph without obscuring one or the other data set. For ease of comparison, Figure 1(b) shows the measured RCS medianized over a 0.5˚ increment. Also plotted in Figure 1(b) are the data generated by XPatch at 0.5˚ increment. Fully polarimetric experimental data were taken with a range resolution of 10." However, to simplify the computation for XPatch, the data shown in Figure 1 are plotted at a single frequency. It can be seen that there is very good agreement between the measured and predicted RCS with the greatest differences being seen on the sharpest features when comparing the XPatch calculation of Figure 1(b) with the un-medianized data of Figure 1(a). This is due to the fact that the predicted data is calculated at a resolution of 0.5˚ which allows significant

under-sampling across narrow features. In comparison, the measured data has been taken at a resolution that is sufficient to capture more detailed scintillation.

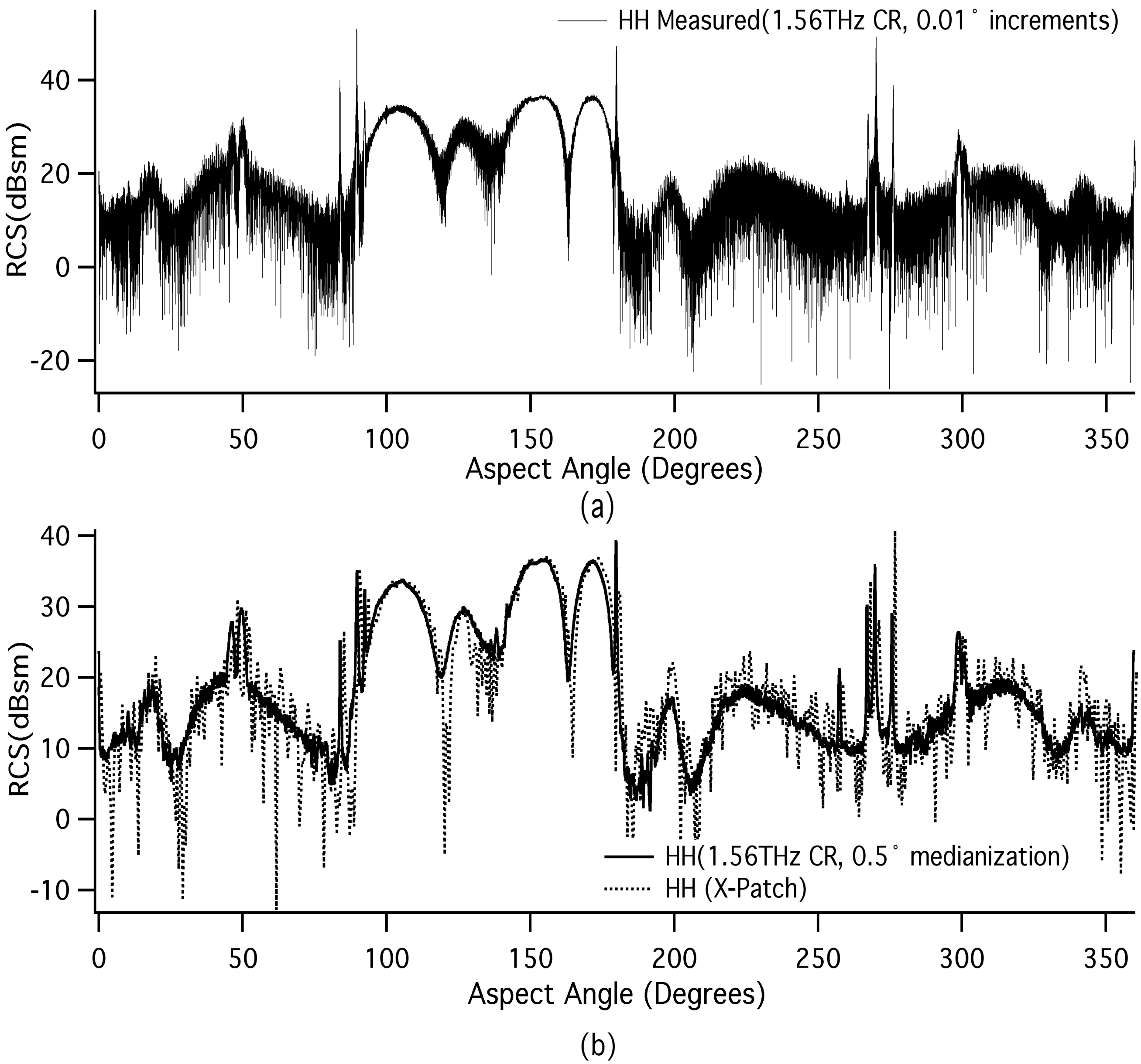


Figure 2. Comparison of experimental and predicted HH RCS for the T5M3 complex target simulator. Figure (a) shows the measured RCS values at 0.01˚ azimuth resolution. Figure (b) shows a comparison of measured RCS medianized at 0.5˚ to the XPatch calculation generated at 0.5˚ increments.

For a further comparison, Figure 3 shows the results for the H transmit V receive channel. It is seen that the computer prediction and experimental data show some differences in the cross-pol. While in the co-pol data there were differences due to the sharpness of the features and the resolution of the calculation, the features showing significant differences in the cross-pols are broad and therefore not subject to that type of effect. For example, near 30˚ aspect angle and also between 60˚ and 70˚, XPatch predicts RCS values about 10dB higher than measured. The differences seen between the plots are significant and suggest that there may be limitations in the current XPatch code for handling linear cross-pol scattering.

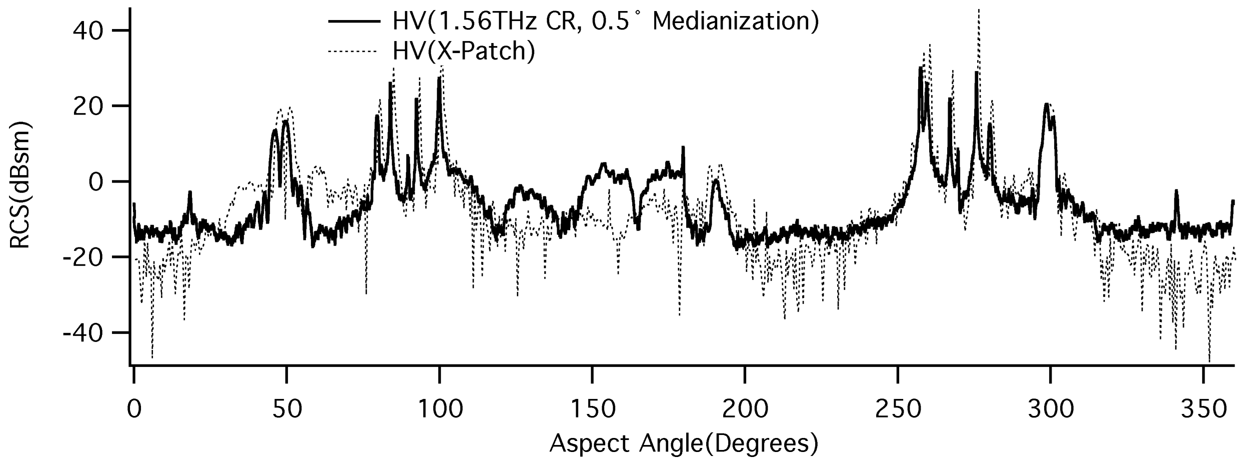


Figure 3. Comparison of Measured H-transmit V-receive RCS and those predicted by XPatch

3.2. Scale model ground terrain.

In order to duplicate the exact conditions of a target on the ground, extensive work has been done to simulate the ground environment. In addition to simulation of the clutter return, the interaction of the electromagnetic radiation with the ground and target can be very significant. Full details of this work are given in Ref[7] of this conference and therefore only a brief description will be given here.

To simulate the desired ground environment, the dielectric and roughness properties of the ground are determined at the frequencies of interest either from in-house microwave measurements or from available literature. Materials are then selected that have these same properties at the scaled frequencies and extensive tests are performed to insure that they reproduce the electrical characteristics of the real ground terrain. A scale model ground terrain is then made and measured in the compact range. The ground terrain is designed to simulate not only the electrical properties of the terrain of interest but also its roughness. The W-band compact range has been used to characterize a large variety of sample ground terrain. Az/El imaging data have been taken continuously from 0˚ elevation to 90˚ elevation. From these images the back-scattering coefficient (commonly referred to as σ_0) is calculated as a function of elevation angle. A sample of these results is shown in Figure 4 for a ground terrain with an index of refraction of 2.6 and full-scale rms surface roughness of 0.46". The full results of these measurements are given in Ref[7]. A smaller data set of fully polarimetric ISAR images has also been taken which verify the results from the Az/El imagery. An example of these results at a 40˚ elevation angle are shown in Figure 5. Using this technique, any desired ground environment can be simulated for a target to be measured on. The calculated σ_0 falls well within the range of values (both in amplitude and shape) that have been measured in previous works[8,9] at W-band.

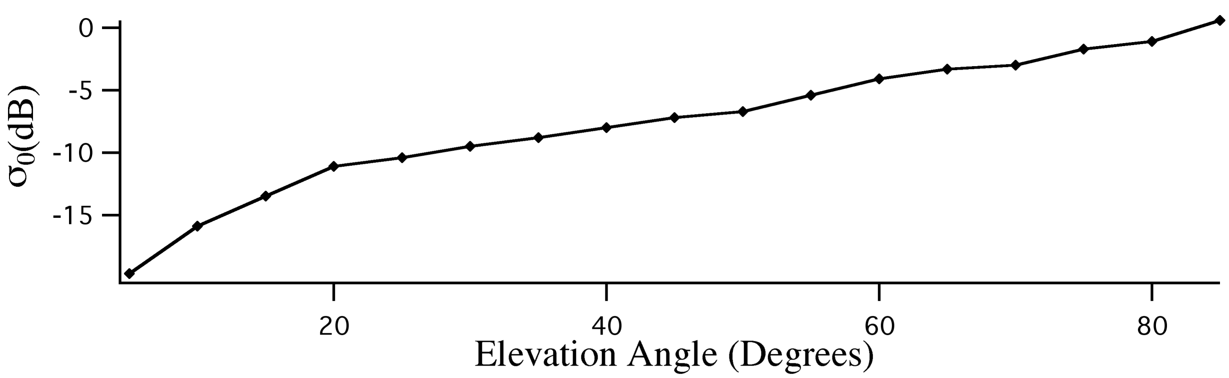


Figure 4. Back-scattering coefficient as a function of angle for a ground terrain with index of refraction 2.6.

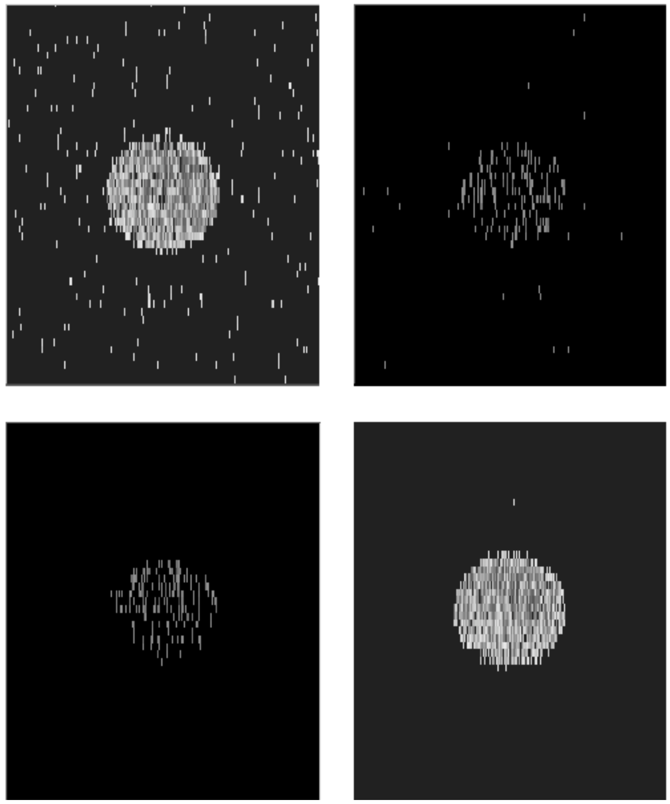


Figure 5. Fully polarimetric ISAR image at 40˚ elevation of simulated ground terrain with refractive index of 2.6 and rms roughness 0.46" at full scale. Clockwise from top are HH, VH, VV, and HV.

3.3. Az./El Images of the T80 tank model from 10˚ to 25˚ elevation.

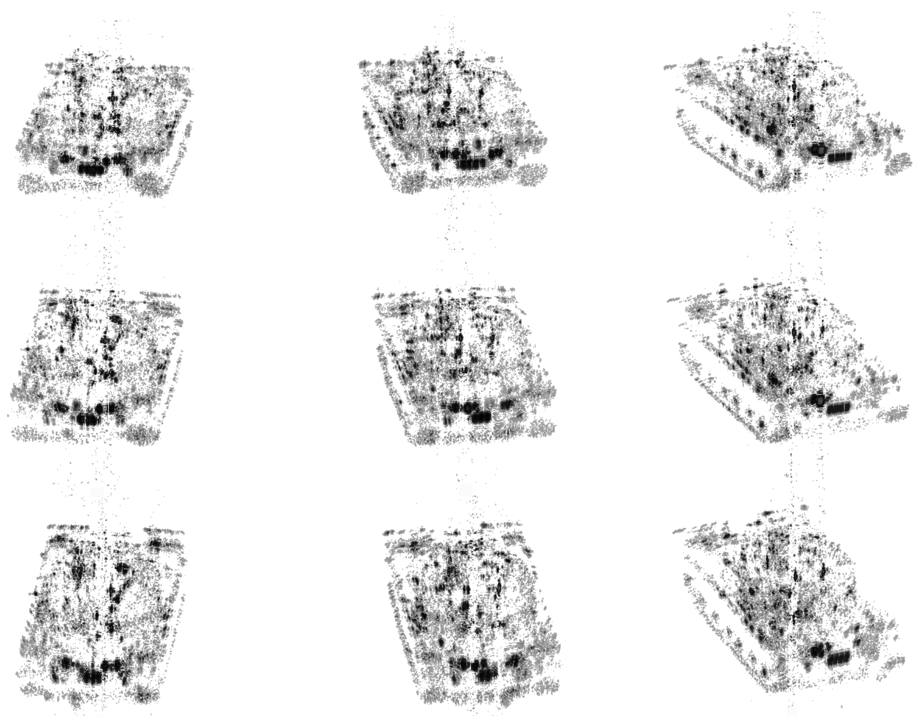


Figure 6. Az/El images of T80 Tank model taken in VV polarization.

Data have been taken on the T80 tank model using the Az/El imaging technique described in Section 2. Single frequency data were recorded in amplitude and phase continuously from 10˚ elevation to 25˚ elevation in 360˚ aspect with a spacing of 0.005˚ in aspect and 0.01˚ in elevation. While range cannot be calculated from a single frequency, the two-dimensional images in azimuth cross range and elevation cross range can be formed continuously at any arbitrary aspect and elevation look angle. This technique will allow data to be collected from 0˚ to 90˚ elevation to form a hemisphere solid angle of data from which any image of the target can be formed. This technique is very useful in identifying individual scatterers on a target. Figure 6 shows several examples of the T80 images formed at slightly different aspect and elevation angles. These images were integrated over a 5˚ by 5˚ angular window and have cross range resolutions of 0.7" on the full scale target.

3.4. ISAR Imagery of scaled model tanks.

As examples, five tank models were measured in the compact range. Fully polarimetric data sets were collected on the Challenger 2, Leclerc, T80, M48 and T55 tank models under several different conditions. All of the data sets presented here were taken using a 0.5s duration frequency chirp of 8GHz bandwidth corresponding to a nominal range resolution of 12" on the full scale target. Since all data were taken in the 4 linear polarization states and since the volume of data was very large, automated data collection and analysis programs were developed. The microwave sweeper that generates the frequency sweep is capable of putting out 1601 individual frequency points. The analysis program pads this number up to the next power of two which is 2048 for the convenience of performing an FFT. The 2048 point FFT gives a 9.2" range resolution in the ISAR images. However, since the data is stored in its unmodified form DFTs may be performed when required at the expense of a longer data analysis time. Due to the sizes of the targets and the high frequency, angular increments of 0.005˚ were required to sample the targets adequately. All data were taken from -10˚ to 370˚ for full coverage and to provide a suitable overlap region. The overlap region also provides a very useful means of verifying the stability of the compact range in amplitude, phase and positioning.

A typical data set is shown in Figure 7 for the T80 tank model measured in free space. The data in Figure 7 has been calculated by incoherently summing the RCS over the target range for individual chirps at a spacing of 0.005˚. For display purposes the data have been medianized using a 0.5˚ median. Figures 8 through 11 show ISAR images generated from these data sets. These figures show the T80, Challenger 2, Leclerc and T55 tank models at several different angles. The targets were measured on a ground terrain that simulated a slightly moist, medium-rough, soil. The shadow that the target casts on the ground terrain can be seen in these figures as well. Figure 9 shows the Challenger 2 tank model at a 20˚ elevation at -10˚ aspect. The turret of the Challenger 2 has been turned approximately 30˚ in this data set to study the effect this has on recognition of the target. The barrel of the main gun can easily be seen in this image. Figures 8 through 11 were formed by performing a Fourier transform across a 5˚ window. This transform gives a cross range resolution of 0.7". Figure 14 shows an example of the ISAR images in false color. Since the data is taken at relatively high frequency, it is possible to achieve very good cross range resolution while still integrating over relatively small angular extents. Figure 14(a) shows the fully polarimetric ISAR for the Challenger 2 formed over a 0.4˚ aspect angle. This process gives square pixels for down range and cross range with a pixel dimension of approximately 9". Figure 14(b) shows an expanded view of the HH channel integrated over 5˚ and the shadow cast on the ground terrain.

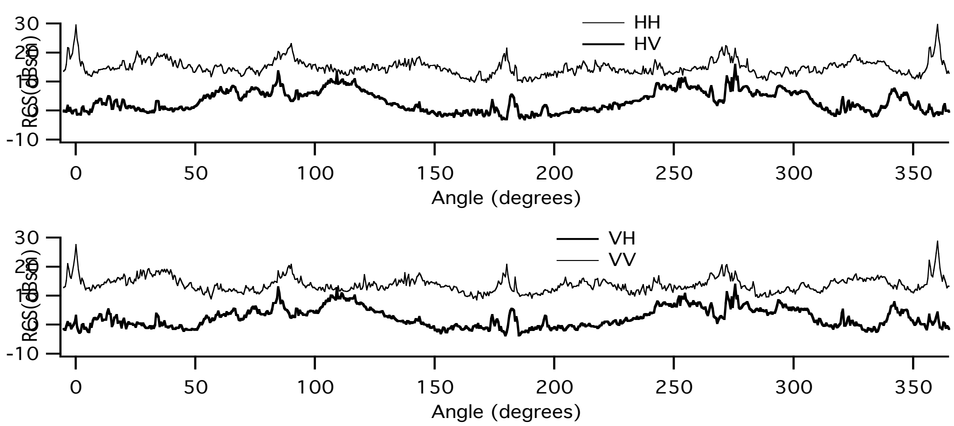


Figure 7. RCS of T80 tank model in free space medianized over 0.5˚.

In order to demonstrate the effect of the ground terrain on the RCS of the target, the T80 tank model was measured both in free space and on the simulated ground terrain. Additionally, in order to test the reproducibility of the system the Challenger 2 tank model was measured on a ground terrain at an elevation angle of 15˚ for two separate measurements which both covered 360˚ in aspect. Figure 13 shows a comparison of the data sets for the Challenger 2 plotted in histogram form. Histogram plots were selected since they allow the differences between the data sets to be displayed without one data set obscuring the other due to the large amount of scintillation. In this figure the RCS of the Challenger 2 has been calculated from the incoherent sum of individual range chirps spaced 0.005˚ in aspect and a histogram calculated for each polarization state. The two data runs display very good agreement in the shape and location of the peak of the histograms, showing that the measurement is highly reproducible. Similar plots for the T80 tank model measured separately in free space and on a ground terrain are shown in Figure 12. It is clear that the presence of the ground terrain results in an approximate 3dBsm increase in the total radar return from the cross-pols of the target. This produces a general shift of the TRCS histograms

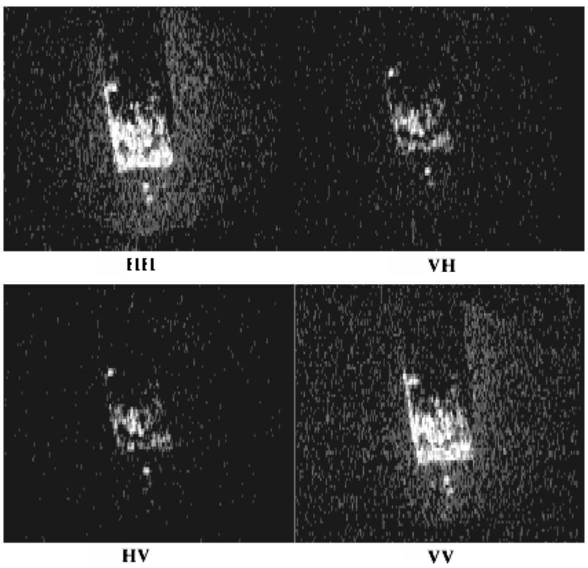


Figure 8. ISAR image of T80 tank model on ground terrain at 350˚ aspect and 15˚ elevation.

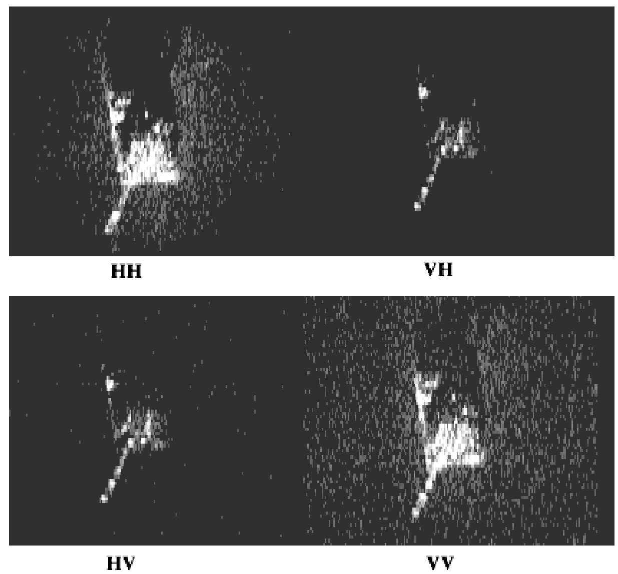


Figure 9. ISAR image of Challenger 2 Tank model on ground terrain at 350˚ aspect and 20˚ elevation. Turret turned 30˚.

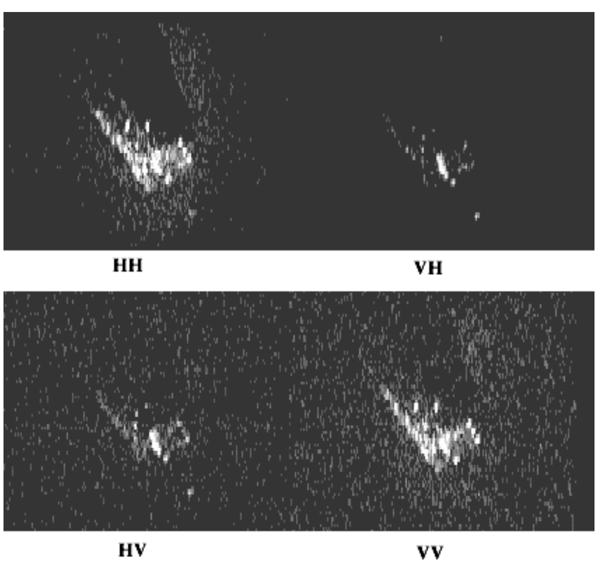


Figure 10. ISAR image of Leclerc tank model on ground terrain at 340˚ aspect and 20˚ elevation.

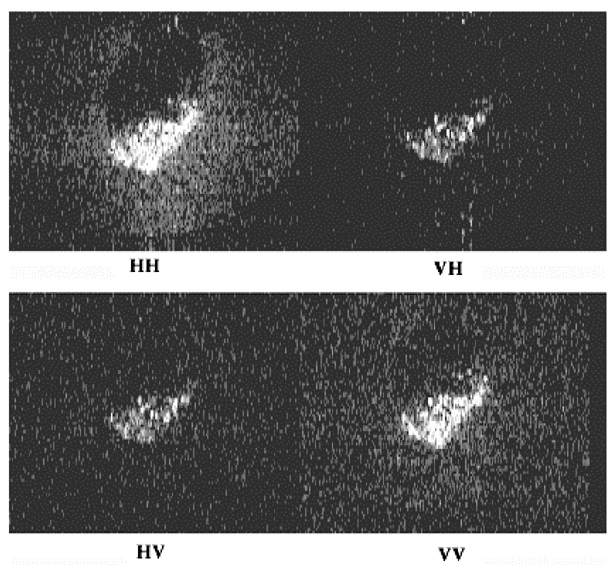


Figure 11. ISAR image of T55 Tank model on ground terrain at 35˚ aspect and 15˚ elevation.

towards higher values. There is also an approximate 1dB increase for the co-pols.

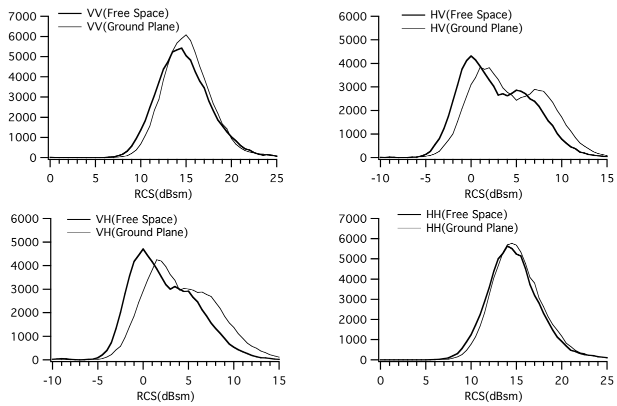


Figure 12. Histogram of TRCS values for the T80 Tank model with and without ground terrain.

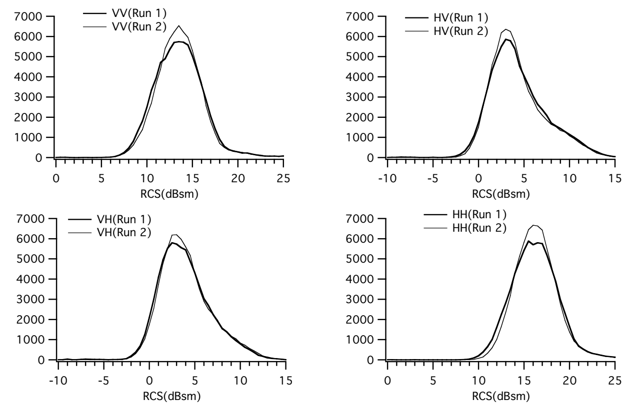


Figure 13. Histogram of TRCS values for the Challenger 2 Tank model for two data sets taken at the same angle.

3.5. 3D ISAR

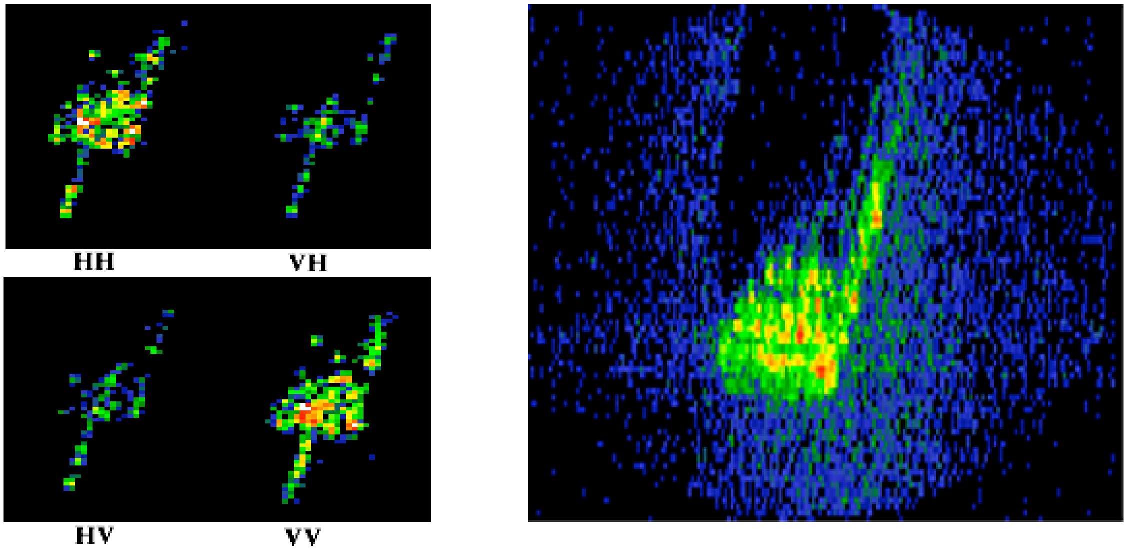
In addition to the two-dimensional imaging techniques described in the previous sections, it is also possible to produce three-dimensional images of a target. Figures 15 and 16 show examples in false color of free-space 3-D data taken from models of the M48 and T55 tanks respectively. The M48 data set was taken at a view angle of 15˚ depression and 30˚ aspect. The T55 data set was taken at 15˚ depression and 330˚ aspect. The imaging technique consists of viewing the target through a two-dimensional aperture in the same fashion as an Az/El image while at the same time performing an 8GHz frequency sweep of 0.5sec duration to measure the range at each Az/El position. Fourier transform of the data yields fully polarimetric scattering information in the down range, horizontal cross-range and vertical cross-range coordinates. Photos of the targets are also shown at approximately the same angles in Figure 17 for reference.

Since the time required to collect the 3-D data is considerably longer than that used for 2-D ISAR, the data can be calibrated in both amplitude and phase to an in-scene object located in a slightly different set of range bins from the target. In this manner, potential longer-term changes in the system and atmospheric effects due to the air-conditioned range can be monitored and corrected if need be. However, during the approximately 2-hours needed to collect the 1.28˚ by 1.28˚ solid angle of data used in these images, the drift of the system was negligible in amplitude and 15˚ in phase, necessitating only a very small correction. It can be seen from Figures 15 and 16 that the resolution in a 1.28˚ integration is very good. Voxel element sizes in these figures are 2.8" by 2.8" by 9.2." Since the target was over-sampled by more than a factor of 2 in elevation and since the signal to noise is also very good it is possible to improve the data collection speed significantly for future measurements. Not only will this increase the speed over which large 3-D data sets can be collected, it should minimize the amount of time over which the system may drift.

To demonstrate the three dimensionality of this data, the HH pol of the T55 tank model is displayed in Figure 15. Figures (a), (b) and (c) show the 3 right angle views of the data (front view, top view, and side view respectively). The voxel noise floor of the 3-D data is approximately -50 dBsm. A similar plot for the M48 tank model is shown in Figure 16.

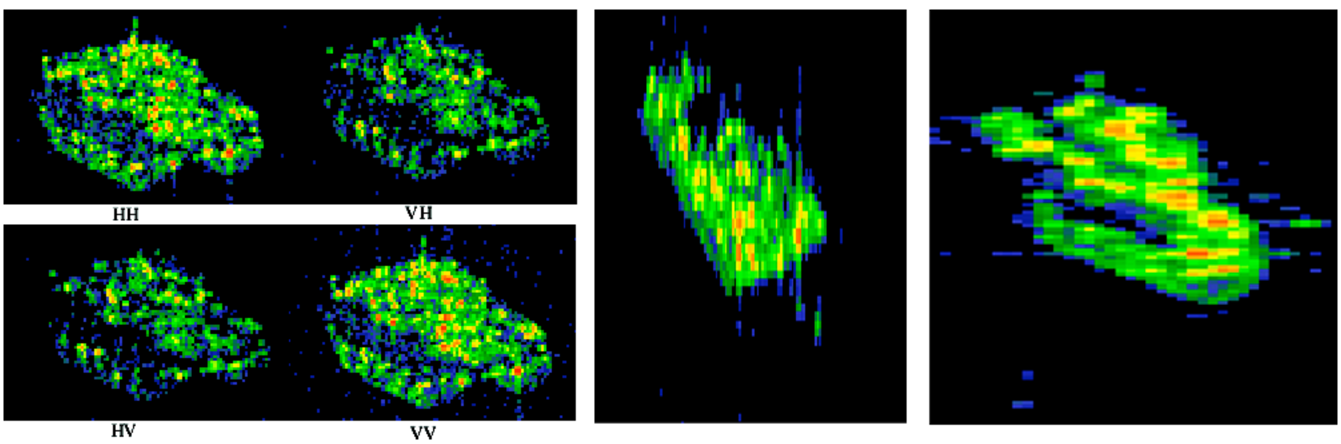
4. Summary

A new fully polarimetric compact radar range operating at 1.56THz has been developed. Model targets can be measured in "free space" or on simulated ground terrain. Measurements have been performed on a complex target simulator and compared with predictions from the XPatch computer code. Polarimetric ISAR data has been taken on five tank models. In addition to the two dimensional ISAR data, the compact range has also collected three dimensional data on several tactical targets. Single frequency data has been taken over large angular extents in azimuth and elevation allowing the formation of very high resolution images in azimuth cross range and elevation cross range.



a b

Figure 14. Challenger 2 tank model ; (a) shows ISAR at 12˚ aspect and 15˚ elevation. (b) shows HH channel at 190˚ aspect and 15˚ elevation.



a b c

Figure 15. Three dimensional data on the T55 tank model; (a) Front View, (b) HH Top View, (c) HH Side View.

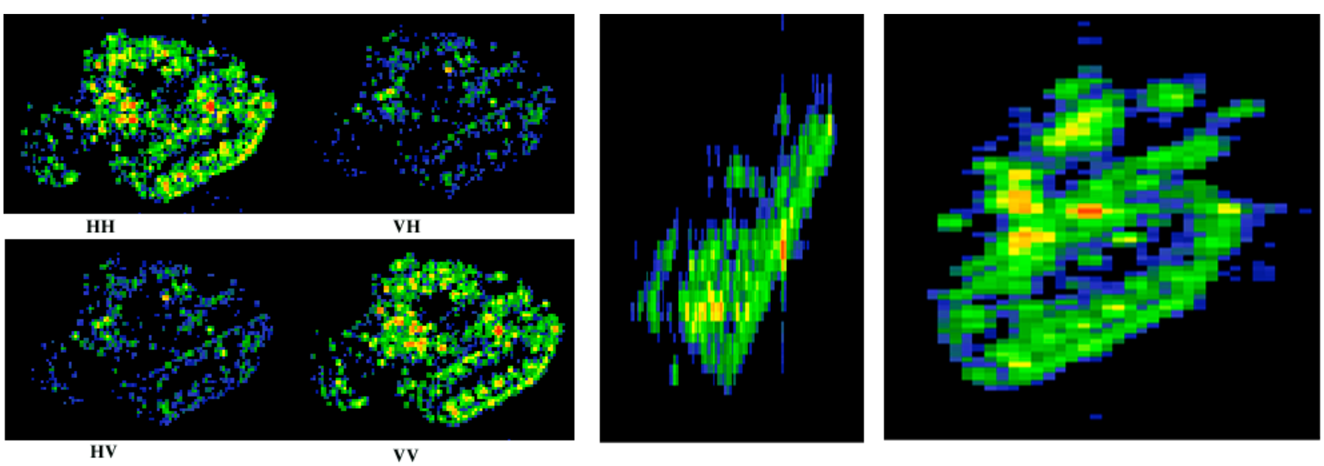


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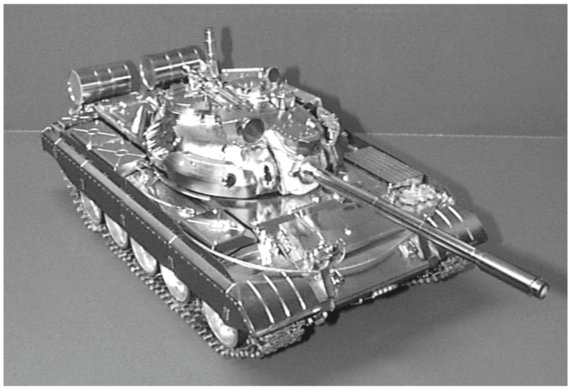
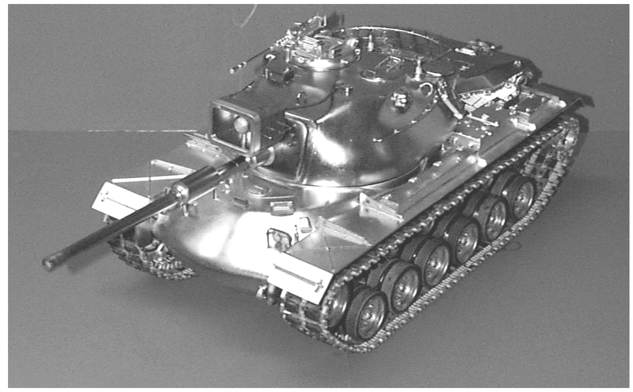
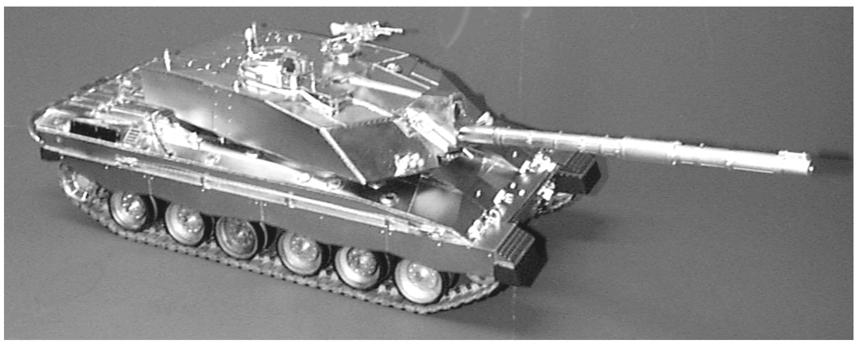
Figure 16. Three dimensional data on the M48 tank model; (a) Front View, (b) HH Top View, (c) HH Side View.



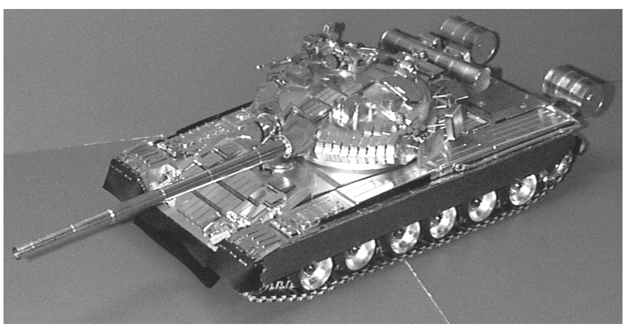
a. T55 Tank.



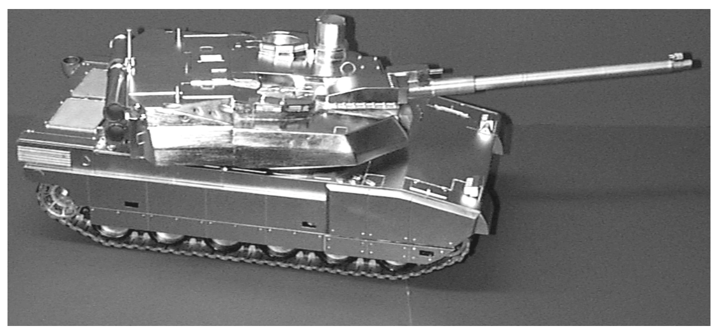
b. M48 Tank.



c. Challenger 2 Tank.



d. T80 Tank.



e. Leclerc tank.

Figure 17. Photographs of scale modeled tanks.

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